PHASE CONJUGATION AND BEAM COMBINATION USING STIMULATED BRILLOUIN SCATTERING

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July 1993

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Final Report

93-20353

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PHILLIPS LABORATORY
Lasers and Imaging Directorate
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

This final report was prepared by the University of Pittsburgh, Pittsburgh, Pennsylvania, under Contract F29601-89-K-0019, Job Order 33261B21 with Phillips Laboratory, Kirtland Air Force Base, New Mexico. The Laboratory Project Officer-in-Charge was Christopher M. Clayton (LITN).
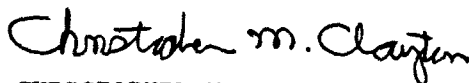
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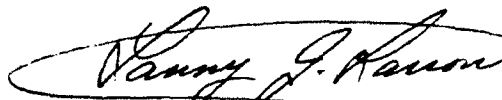This report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1993	3. REPORT TYPE AND DATES COVERED Final, 21 Apr 89 - 31 Jan 92

4. TITLE AND SUBTITLE

PHASE CONJUGATION AND BEAM COMBINATION
USING STIMULATED BRILLOUIN SCATTERING

6. AUTHOR(S)

Joel Falk and Morton Kanefsky

5. FUNDING NUMBERS

C: F29601-89-K-0019
PE: 62601F
PR: 3126
TA: 1B
WU: 21

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Pittsburgh
348 Benedum Hall
Pittsburgh, PA 15261

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Phillips Laboratory
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

PL-TR--93-1007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report summarizes work performed on the use of stimulated Brillouin scattering for phase conjugation and beam combination. The mutual coherence between two stimulated Brillouin signals produced by two, partially overlapped pumped beams is studied both experimentally and theoretically. In addition, the transient buildup of a phase conjugate Stokes beam is described using a zero-order numerical solution to the governing equations.

14. SUBJECT TERMS

Phase conjugation, Beam combination, Stimulated Brillouin
Scattering, Nonlinear optics

15. NUMBER OF PAGES
30

16 PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19 SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR

PREFACE

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INTRODUCTION

In recent years well-known nonlinear optical effects have found new uses. In particular, stimulated Brillouin scattering (SBS) has been used for image aberration correction, pointing and tracking enhancement, and beam combining.

The work at the University of Pittsburgh has centered on the investigation of phase conjugate devices. The two central questions that were asked in the research program are: what determines the accuracy of phase locking of multiple laser beams (i.e., what determines the usefulness of SBS for beam combination) and what are limits to the fidelity of the phase conjugate SBS process?

PHASE LOCKING AND BEAM COMBINATION: THEORY

In recent years there has been a growing interest in finding ways to combine multiple lasers into a single, high-brightness beam. This interest stems from a need to overcome limitations to the power which can be extracted from a single gain medium (Refs. 1-3). To be combined effectively, the beams must be mutually coherent in both space and time.

The formation of two SBS beams generated in partially overlapped volumes was analyzed. The mechanism for the coupling between two SBS outputs was examined and was shown to be four-wave mixing. The statistical nature of the coupling was characterized by the probability density function (pdf) of a mutual coherence function (mcf) and its dependence on pump beam overlap, phonon lifetime and pump pulse-duration was determined.

The experimental arrangement considered is shown in Figure 1. Two strong pumping beams, E_1 and E_3, are incident upon a Brillouin active medium. The pump beams are assumed to be undepleted as they generate backscattered Stokes outputs, E_2 and E_4. The pumping beams are partially overlapped and each interacts with both Stokes outputs. Figure 1a shows nonparallel pump beams E_1 and E_3; Figure 1b shows parallel, but not completely overlapped

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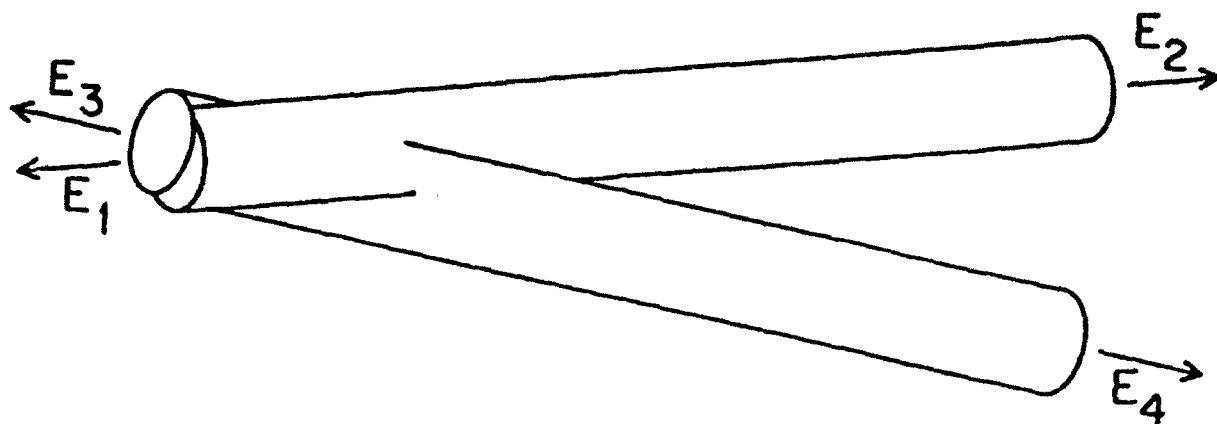
(a) Nonparallel pump beams, E_1 and E_3.
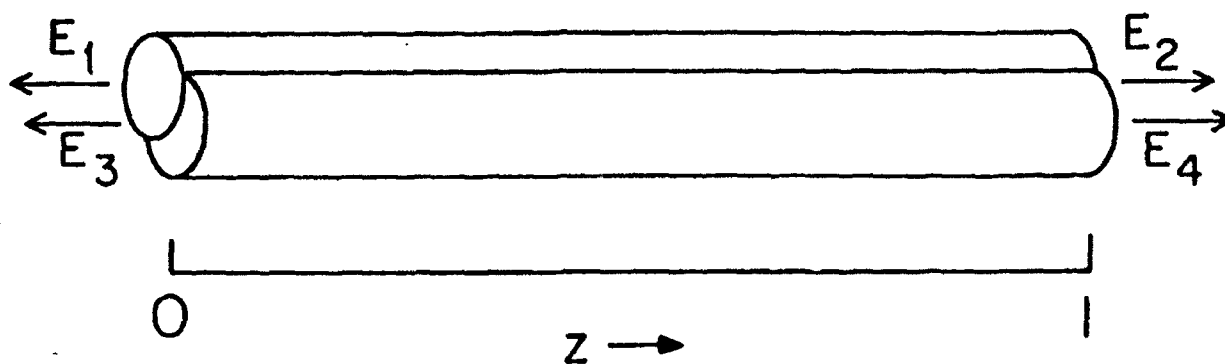
(b) Parallel pump beams.

Figure 1. The SBS beam generation. (The Stokes beams are designated E_2 and E_4. The arrows indicate the direction that the Stokes and pump beams follow as they emerge from the SBS medium.)

pump beams. The configuration shown in Figure 1a has been actively investigated. The arrangement of Figure 1b, while not yet used for beam coupling, is the limiting case of Figure 1a for small beam intersection angles.

The Stokes outputs are determined by Maxwell wave equations driven by polarizations that are nonlinear in electric field. The polarizations are due to the interaction of the pump fields with acoustic waves. The acoustic waves are caused by optically induced density fluctuations in the medium. The Stokes fields build out of thermal-acoustic noise and grow as they propagate.

The mutual coherence of the two SBS beams can be evaluated by overlapping and combining the two beams and measuring the resulting energy output. The mcf is defined by:

$$S = \frac{F_0}{\sqrt{F_2 F_4}} \tag{1}$$

where the output energy for pulses with a duration of T_p sec is $F = F_2 + F_4 + F_0$ where

$$F_{2,4} = (1/2\eta_0) \int \int |E_{2,4}|^2 d^2r_\perp \, dt \tag{2}$$

and the interference between Stokes beams 2 and 4 is measured by

$$F_0 = (1/4\eta_0) \int \int [E_2 E_4^* + E_2^* E_4] d^2r_\perp \, dt = (1/2\eta_0) \int \int |E_2||E_4| \cos \phi \, d^2r_\perp \, dt \tag{3}$$

where ϕ is the phase difference between the Stokes beams, η_0 is the intrinsic impedance of free space (377 Ω) and the spatial integrals are over transverse cross section.

If the Stokes beams are phase conjugates to their collinear pump beams then the spatial variations of the Stokes beams will follow those of the pumps (Ref. 4). If the two pump beams are identical, then the phase difference ϕ will be independent of transverse dimension $r_\perp$, but will still vary randomly in time. For completely mutually coherent Stokes beams, $\phi = 0$ and $S = 1$. For independent Stokes beams, ϕ will be uniformly distributed between 0 and 2π and $-1 \leq S \leq +1$ with an expected value of 0.

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In the theoretical work, the mutual coherence of two SBS Stokes beams produced by partially overlapped pump beams was investigated. Because the Stokes outputs originate from thermal-acoustic noise, the absolute phase of the output beams is a random variable or random process and the degree of mutual coherence between the two beams must be described by a pdf. The two Stokes outputs were shown to be partially correlated as a result of four-wave-mixing. The mathematical description of each Stokes output consists of two terms: a high-gain solution and a low-gain solution. For nearly parallel, partially overlapped pump beams, the high-gain solution usually dominates (even for moderate pump beam overlaps) and the two Stokes outputs are nearly perfectly correlated. For parallel pump beams, the correlation coefficient ρ between the two Stokes outputs can be calculated directly. For nonparallel pump beams, ρ must be calculated numerically and it depends on the size of the overlap region and the laser pulse intensity. Correlation between the Stokes outputs is produced by four-wave-mixing in the region where the pump beams are overlapped. The SBS gain outside of the overlap region, spectrally narrows the Stokes outputs but does not change ρ. For both parallel and nonparallel pump beams the correlation coefficient, the steady-state gain G, and the ratio of laser pulse duration to phonon lifetime T_p/τ_{phonon} determine the pdf of the mcf. For short laser pulses, the mcf reduces to $\cos \phi$, where ϕ is the phase difference between the two Stokes outputs and the pdf of this mcf can be calculated analytically. Further details of the theoretical beam combination work are given in Reference 5.

The theoretical work is consistent with the experimental work reported in the literature including the experimental work carried out in this program. Details of experimental beam combination program are given next.

PHASE LOCKING AND BEAM COMBINATION: EXPERIMENT

Recent experimental studies of SBS for combining laser beams have shown that Stokes beams with essentially the same temporal phase can be generated from multiple laser pumping beams if the input beams are spatially well overlapped (Refs. 3 and 6-11). Poor phase-locking (or the absence of locking) is observed if the pumping beams are not well overlapped.

The experimental work accomplished in this program demonstrates that the physical mechanism for the observed phase-locking is four-wave-mixing and that beam coupling is not merely the result of the partially overlapped pumping laser beams leading to overlapping acoustic beams.

Two strong pumping beams, E_1 and E_3 (and in some experiments a seed beam E_2 counterpropagating to E_1), are incident upon a Brillouin active medium (Fig. 1). The pumping beams are assumed to be undepleted by the SBS interaction which produces two backscattered Stokes outputs, E_2 and E_4. The pumping beams are partially overlapped so that both input beams interact with both Stokes beams. The angle between the pumping beams is small but nonzero.

The degree of phase locking between the Stokes outputs was examined by the dependence of phase-locking on the polarizations of seed, pump, and output Stokes beams. An mcf S measures the degree of phase locking between E_2 and E_4. The function S quantifies the degree of spatial and temporal coherence between the two outputs and is calculated from:

$$S_i = \frac{\int |E_{2i}| |E_{4i}| \cos\phi \, d^2r \, dt}{[\int |E_{2i}|^2 d^2r \, dt \quad \int |E_{4i}|^2 d^2r \, dt]^{1/2}}. \tag{4}$$

The amplitudes of the Stokes output E_2 and E_4 are measured in a plane where the two outputs are overlapped. The angle ϕ is the temporal phase between the E_2 and E_4. The integrals are over spatial cross section (d^2r) and time (dt) (Refs. 5 and 12). In some experiments, the coherence function is different for the Stokes polarizations parallel and perpendicular to a seed beam. To indicate this polarization dependence we have written S_i, E_{2i}, and E_{4i} were written where $i = x, y$ indicates the polarization of the Stokes fields recorded. In general, because the Stokes outputs are amplified noise (Ref. 4), the mutual coherence S is a random variable and must be described by its statistics. For Stokes beams totally phase-locked S = 1; for beams generated in independent volumes, S has values distributed between -1 and +1.

The pdf of S was examined for seeded and unseeded SBS systems and for various polarizations of pump and seed beams. The phase-locking with and without a seed beam was investigated for parallel and perpendicularly polarized pump beams. For the unseeded case, phase-locking was found for parallel polarized pump beams and no locking for orthogonally polarized pump beams. These results are reported in Reference 12.

In the seeded case, the seed beam sets the temporal phase for each Stokes beam that it drives. For example, locking is observed when pumps and seed are polarized in the same direction. For orthogonally polarized pump beams, a different behavior is observed for each of the two perpendicular Stokes polarizations; locking is observed for one output polarization but not the other. The experiments done on this program help to elucidate the physics of phase locking and role of four-wave mixing in multibeam SBS.

Stimulated Brillouin scattering was produced in ethyl alcohol using a frequency-doubled, Nd:YAG (532 nm), 7-ns, 10-pps laser. The laser ran single-longitudinal mode on a significant fraction of its output pulses and our data collection system was gated so that data were recorded only when the laser produced the narrow-bandwidth, single-mode output. As shown schematically in Figure 2, a phase grating was used to split the incident laser beam into many orders (Refs. 9 and 12). Two grating orders were focused into a 2-cm diameter and 25-cm length cell containing ethanol. A half-wave plate ($\lambda/2$) was sometimes used to rotate the nominally horizontal (x) polarization of pump beam E_3 by 90 deg. A horizontally
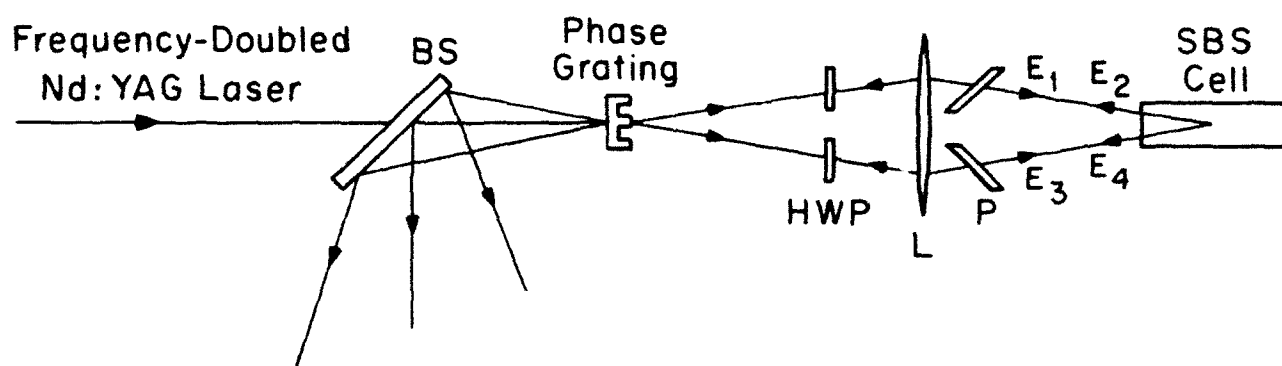
Figure 2. Diagram of the experimental setup. (Pump beams E_1 and E_3 produce output Stokes beams E_2 and E_4. L, lens; BS, beam spliter; HWP, half-wave plates. Quartz plates P are rotated to maximize the overlap between the pump beams.)

(x) polarized seed beam was sometimes generated in an auxiliary SBS cell and passed through a second half-wave plate and used to seed the Stokes beam E_2 with a vertically (y) polarized input.

The two SBS Stokes return signals were recombined in the grating. The energy in the vertical and horizontal polarizations for each of three output orders from the grating was measured on a large number of pulses. The detection system used silicon detectors, gated amplifiers, A/D converters, and a microcomputer. These measurements, along with measured grating parameters, allowed the determination of S_i (Eq. 4) on each laser pulse (Refs. 5 and 12). To form the probability distribution of S, its value for each of 10^3-10^4 laser pulses was calculated and these measured values were sorted into 200 bins equally distributed between +1 and -1. A histogram of the number of pulses in each bin is proportional to the pdf of S. Consequently the plots of fractional number of counts versus bin number are, in effect, plots of the pdf of S.

The first experiments examined an unseeded system with pump beams polarized parallel or orthogonal to each other. For parallel (x) polarized pump beams, the half-wave plate is rotated so that the polarization of the pump beam E_3 is not affected. The Stokes outputs are horizontally (x) polarized and strongly locked together. The resulting distribution of S is clustered near bin 200 (S = +1). For orthogonally polarized pump beams, no locking is observed and S is nearly uniformly distributed between bin 0 and 200 (between S = -1.0 and +1.0). Figure 3 shows the pdf's for S (Ref. 12). The narrow distribution seen for parallel polarized pump beams is indicative of good phase-locking, i.e., the phase angle ϕ varies little from laser shot to laser shot. A widening of the distribution of S is a signature of poor phase-locking, e.g., the distribution seen in Figure 3 for orthogonal pump beams. The location of the peak of the pdf near bin 200 (parallel polarized pump beams) is indicative of the fact that the spatial profiles of E_2 and E_4 are nearly identical, presumably near phase conjugates to their identically shaped pump beams, E_1 and E_3. It is clear from Equation 4 that a shift in a narrow distribution away from bin 200 would be a signature of incomplete spatial overlap between the Stokes outputs.
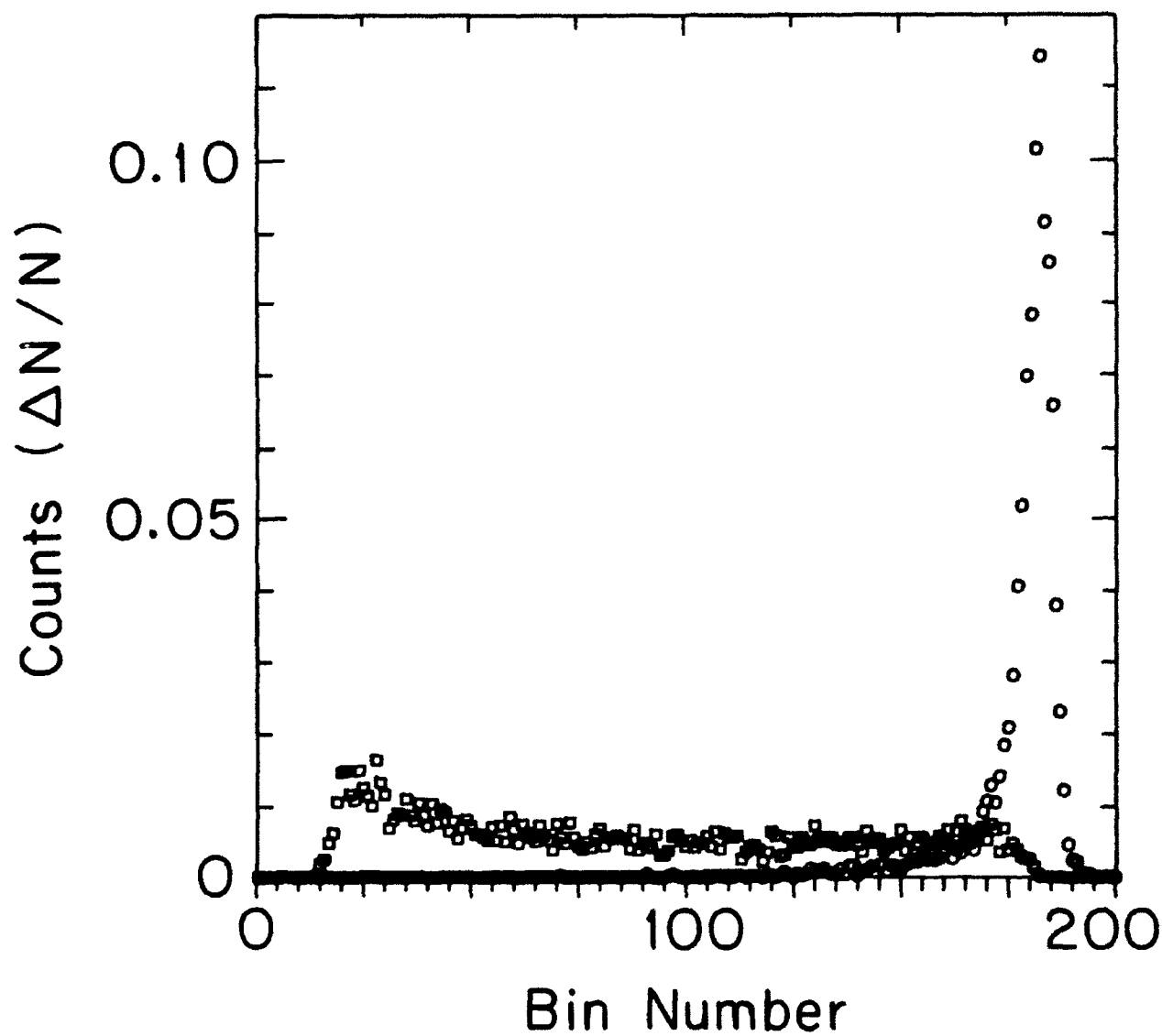
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Figure 3. The pdf of the mcf S for parallel polarized pump beams (○) and perpendiculaly polarized (□) pump beams. (No SBS seed beam was used.)

Later experiments examined a seeded, two pump-beam system. For both pump beams and the seed beam polarized horizontally and parallel to one another, the measured distribution of S is shown in Figure 4. The narrow distribution of S indicates strong phase-locking. The distribution is not centered near bin 200 (S = +1) because of the poor spatial overlap between the seeding Stokes beam and the pump beams. Although the foci of the pump and seed beams had a common center and occurred in roughly the same plane, the pump beam's radius (50 μm) was substantially smaller than that of the seed beam (500 μm). Poor overlap causes poor conjugate fidelity which results in poor spatial coherence between E_2 and E_4 which moves the recorded distribution away from S = +1. However, good phase-locking, as denoted by the narrow width of the distribution, is maintained. Seeded SBS systems behave as seed amplifiers rather than as phase conjugators and thus multiple SBS outputs are not nearly spatially identical (Ref. 10).

For pumping beams polarized perpendicular to each other, i.e., E_1 polarized horizontally (x) and E_3 polarized vertically (y) and a seed E_2 polarized in the y direction, the measured distribution depends on the Stokes polarization observed. All of the x-polarized components (polarizations measured at the detectors) are described by and arise from normal SBS. These Stokes components have no means of exchanging phase information and neither phase locking nor any influence of the seed beam on S_x is observed. The S_x is nearly uniformly distributed over the range -1 to +1. The y components are due to four-wave mixing. The y-polarized outputs, E_{2y} and E_{4x}, are both driven by the input seed, thus both outputs carry its optical phase and are locked together. These outputs have optical phases that are set by the seed beam and a narrow distribution of S results. Poor spatial overlap between the seed and pump beams results in a peak well removed from S = +1 (bin 200). However a sharp peak and small distribution width are seen which indicate good phase-locking. Further details describing this experimental work are given in References 9 and 12. *

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* Hua, X. and Falk, J. "Polarization dependent phase-locking in stimulated Brillouin scattering systems," submitted for publication in Applied Optics, 1993.
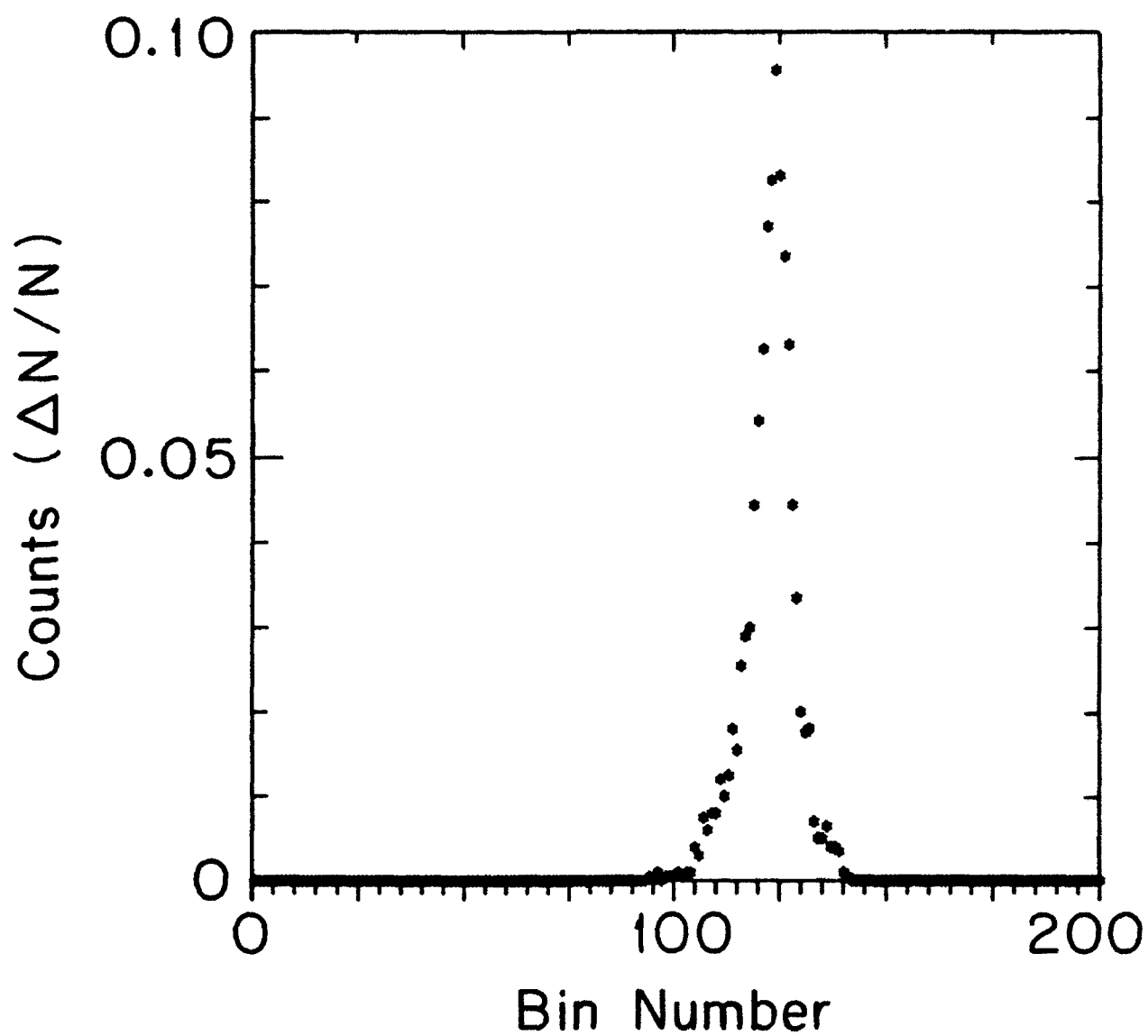
Figure 4. Distribution of S for the dual pump-beam, seeded SBS system. (The pump and seed beams are all polarized in the same [horizontal] direction.)

TRANSIENT SBS PLANE WAVE EFFECTS

Stimulated Brillouin scattering has been studied over the past several decades because of its potential applications in optical image processing, image distortion correction, laser fusion, laser pulse compression, and beam combination. Theories are well developed for SBS if the transverse variations of electric fields are ignored. For the steady state (Refs. 13-16) closed form analytical solutions, including pump depletion, exist. In the transient regime, the slowly varying envelope approximation (SVEA) allows solutions for the Stokes field to be calculated if pump depletion is negligible (Refs. 17-19). Many discussions of SBS oscillators (as well as all discussions of SBS amplifiers) treat the Stokes output as arising from amplification of an input signal that propagates in the opposite direction to an input pump beam. The solution of the governing differential equations then requires the consideration of a two-point boundary value problem (TPBVP).

In the depleted pump, transient regime, even ignoring the spatial variation of electric fields, the TPBVP has not been treated analytically but has been studied numerically. The numerical simulations use a new, efficient, noniterative algorithm which increases the speed of computation over that obtained with the method of characteristics. We study transient SBS seeded by a backward traveling Stokes probe beam. We include the effects of pump depletion and of a finite phonon lifetime τ_p. The phonon lifetime plays an important role in the transient regime. It introduces a memory and hence a delay into the process of energy transfer between the pump and the Stokes beams. The finite phonon lifetime is responsible for the decaying oscillations found in the depleted pump and Stokes output intensities reported here for the first time. Oscillations that appear to be similar to those reported here have been observed by Munch et al. (Ref. 20).

In the (backward wave) stimulated Brillouin process, a sudden change in pump intensity takes a finite time (delay) to affect the Stokes field, whose response takes a similar time to change the pump. This delay is a consequence of the opposite propagation directions of the pump and Stokes fields and can be caused by either propagation times or by nonzero phonon

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lifetimes (i.e., energy decay times). The existence of this time delay or interaction time implies that if the pump beam is depleted, both its and the Stokes' intensities can overshoot their steady-state values. Thus a transient oscillation can result whose period is equal to the interaction time. For the adiabatic case, where the phonon lifetime is small ($\tau_p \to 0$), an interaction time (twice the time it takes for the pump to propagate from one end of the medium to the other) occurs because of the Stokes and pump beam propagation times. These oscillations have been predicted by Marburger (Ref. 21) and are called finite-cell oscillations. Oscillations in backward wave SBS associated with interaction times related to the energy storage time or the phonon lifetime of the system were analyzed. These oscillations do not occur for forward (e.g., Raman) scattering.

Simulations are carried out for both step-like and Gaussian pump pulses. The Stokes input is assumed constant during the entire pumping period.

Figure 5 shows both the output of the pump intensity at $z = 0$ and of the Stokes intensity at $z = L$ for a step pump and an initial (normalized) Stokes intensity of 10^{-16}. The numerical values chosen imply steady-state power gains, ignoring depletion, of $\exp(50)$. A decaying oscillation is seen in the pump and the Stokes outputs during the transient regime. For most simulations, the phonon lifetime is large enough so that the oscillations related to energy storage are important and dominate finite-cell oscillations. The oscillation period for simulations of the type seen in Figure 5 is proportional to the phonon lifetime. The proportionality constant varies linearly with the depleted, steady-state, value of the pump output intensity.

A comparison of the results of the simulations for large t to the steady-state analytical theory (Ref. 13) shows nearly perfect agreement. A comparison of the numerical results in the transient, low-gain regime (where significant pump depletion is not seen) to the calculations based on analytical expressions for the undepleted case (Ref. 18), also shows near perfect agreement. Further details are given in Reference 22.
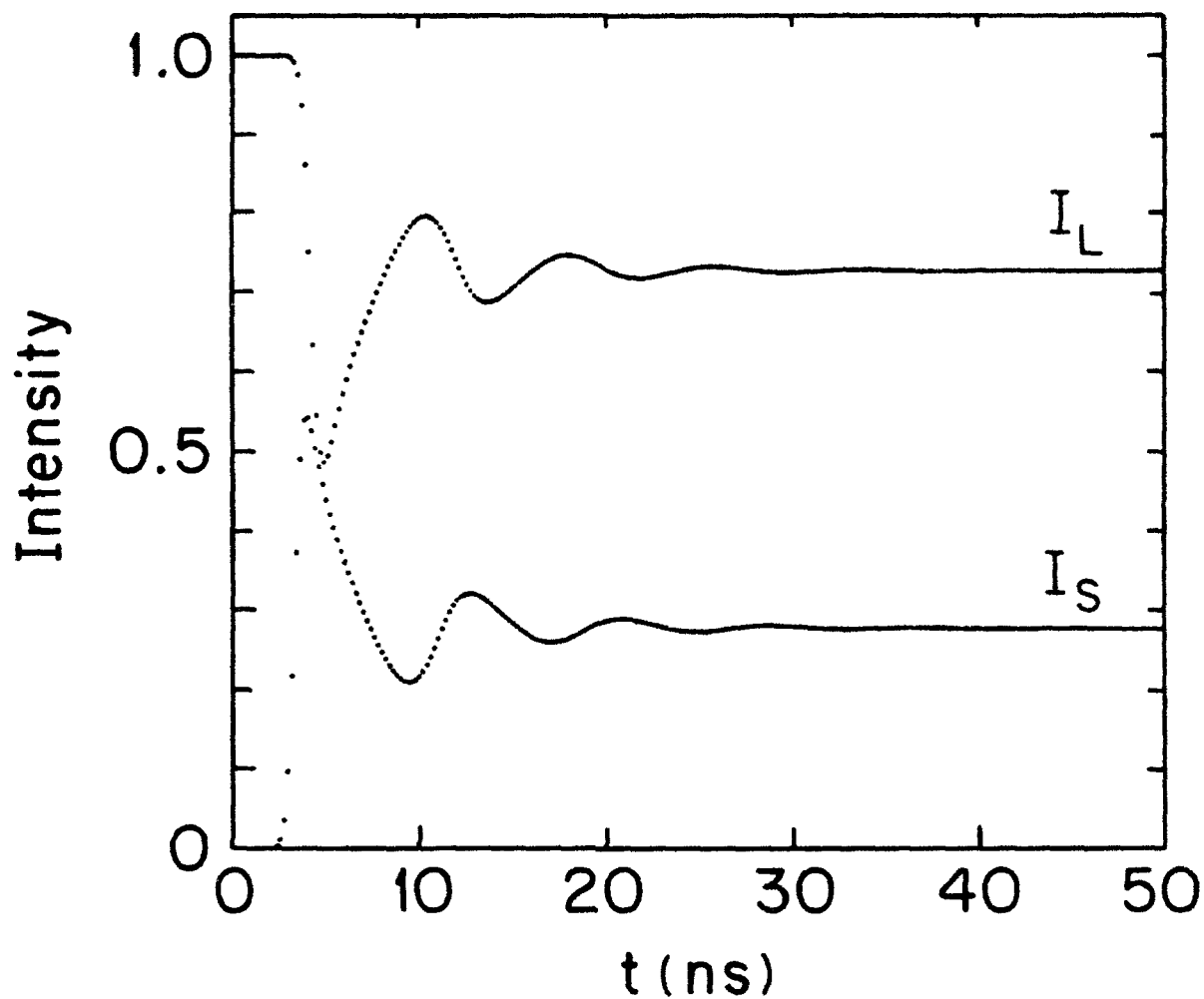
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Figure 5. Typical simulation results: Pump $I_L(z = 0)$ and Stokes $I_S(z = L = 25$ cm) output intensities. The pump is assumed a step pulse. $(G = 50, I_{s0} = 10^{-16}, \tau_p = 0.167$ ns)

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TRANSIENT SBS PHASE CONJUGATION

Phase conjugation by SBS is useful for the correction of phase aberrations (Refs. 23 and 24). Of particular interest is the size of the phase conjugate fidelity and of the SBS reflectivity (Refs. 25-28). Most analytical or computational treatments of the phase conjugation by SBS reduce the complexity of the governing equations by considering only steady-state solutions (Refs. 26-29).

The work presents a numerical simulation of the transient phase conjugate SBS process. The buildup of the SBS phase conjugate output is traced from noise to the steady-state. Phase conjugate fidelity and SBS reflectivity are calculated as a function of time. Most previous steady-state numerical simulations of phase conjugation by SBS, as well as those presented here, consider the buildup of a Stokes output from noise entering one end of the SBS medium. A high-power laser pump field enters from the other end. Because the two input fields enter the medium from opposite ends, a TPBVP problem results. Some of the earliest SBS phase conjugate numerical simulations, published by Lehmberg (Refs. 22, 25, and 29), and recent extensions of his work (Refs. 26 and 28) solved the TPBVP iteratively. An assumed solution for the pump field (as a function of propagation distance) was used to calculate the Stokes output. The Stokes output was then used to find a corrected pump field variation and the process was repeated until the pump and Stokes fields calculated from successive approximations were essentially identical. This iterative approach requires many solutions of a multidimensional differential equation and is computationally expensive, often requiring hours of CRAY supercomputer cpu time. In 1989 Hu et al. realized that the computational complexity of the phase conjugate SBS problem could be greatly reduced if the pump and Stokes fields were expanded in waveguide eigenmodes and if only phase matched terms in the Maxwell wave equation were retained (Ref. 26).

The present work is an extension of Hu's work to include the transient regime. Stokes and pump fields are expanded in waveguide modes. Phase-mismatched terms are neglected and a zero-order approximation of the Maxwell wave equation is simulated. The techniques for

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simulation of the zero-order solution closely follow our earlier work which described the simulation of the depleted pump, plane wave, SBS equations (Ref. 30).

The SBS process to be analyzed is shown schematically in Figure 6. Phase conjugation occurs inside of an optical waveguide. The wavefront of the pump beam is intentionally perturbed by passing the beam through a phase aberrator. Most theoretical treatments and some experimental investigations of SBS phase conjugation show that the phase conjugate fidelity is improved by this use of a phase aberrator. The aberrator is described by its random phase delay and the correlation of that phase delay from point to point across its transverse dimension. The phase aberrations are transformed into intensity aberrations as the pump beam travels through a distance of empty space or empty waveguide. This aberrated beam is incident upon the dielectric waveguide filled with the Brillouin material. The pump field interacts with traveling, material density fluctuations, i.e., with an acoustic wave, and a backward traveling Stokes polarization wave is produced.
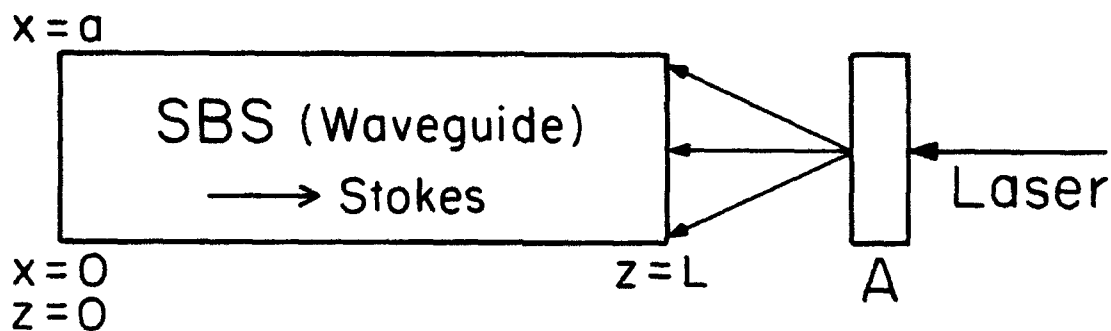

Figure 6. The SBS cell and coordinates. (A=aberrator. The waveguide's cross-section extends from x = 0 to x = a.)

The transient SBS equations under the SVEA are considered. The pump and Stokes fields in waveguide modes were expanded and the SBS equations were solved at each increment in time. The variation of the fields with time was found recursively.

The 2-D transient SBS process was simulated by developing this recursive algorithm that solves the zero-order equations without the need for iteration. When the pump laser field is sufficiently aberrated, the simulations accurately describe the transient SBS phase conjugation process.

The variation of conjugate fidelity and reflectivity with time are determined. Conjugate fidelity builds rapidly. For high gains the fidelity can exceed 0.95 percent in less than several phonon lifetimes. The amplitude of the Stokes field builds more slowly. Its steady-state value is reached in tens of phonon lifetimes.

The initial simulations were directed toward reproducing the results of published simulations. Earlier work by Hu (Ref. 26) and by Lehmberg (Refs. 22, 25, and 29) analyzed steady-state conjugate fidelity and Brillouin reflectivity. The first simulations attempted to duplicate their results. Computer runs were made using gains $gI(z = L)L$ of 5, 6, 7, 8, 10, 12, 15, 17 and 20. The steady-state conjugate fidelity and reflectivity are shown in Figure 7. The agreement with Hu's steady-state simulations, also shown in Figure 7, is excellent (Ref. 26).

Figure 8 shows typical transient behavior of the conjugate output. This figure shows that the transient fidelity builds up rapidly, reaching its steady-state values in several nanoseconds. The SBS reflectivity, in accordance with plane wave calculations, takes tens of phonon lifetimes to reach its steady-state values (Ref. 30). Further details of this work are given in an article submitted to the Journal of the Optical Society of America B.
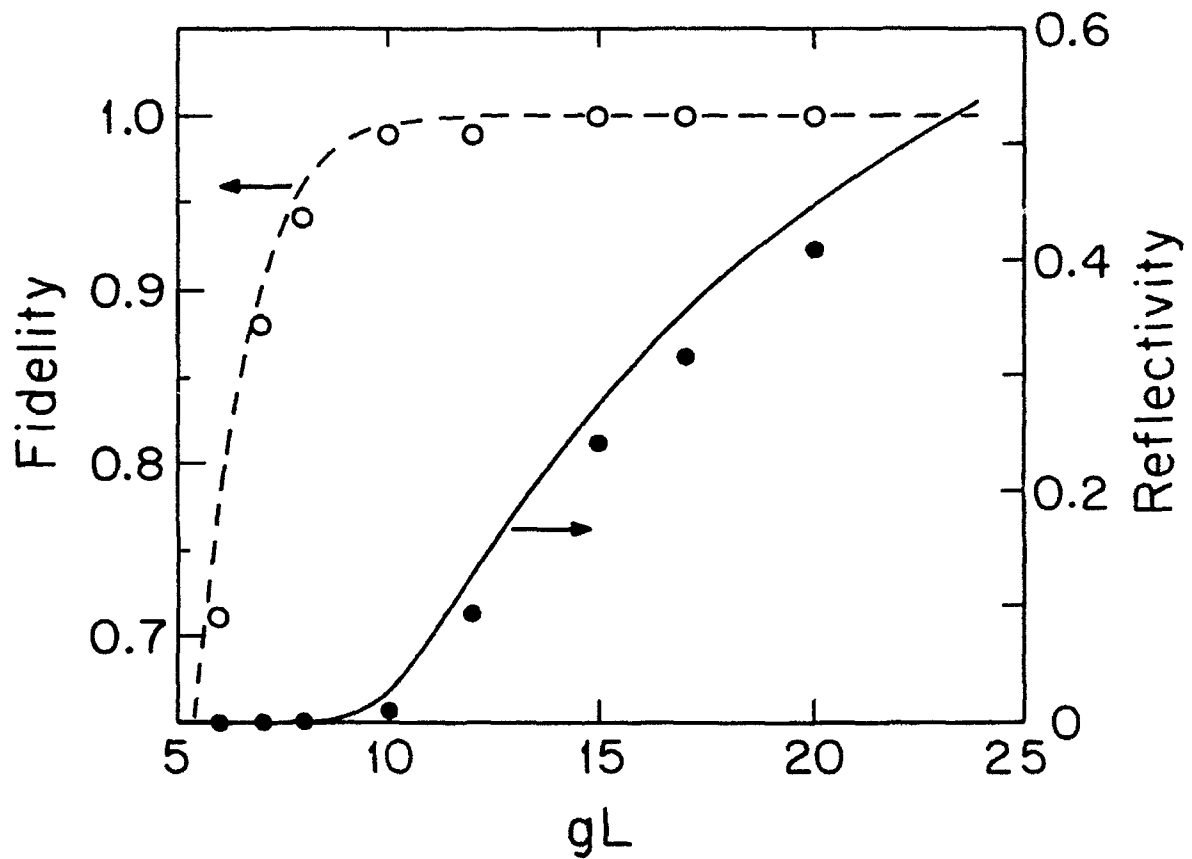
Figure 7. Fidelity, reflectivity at the steady state. An initial Stokes intensity ($z = 0$) 10^{-8} of the pump input ($z = L$) intensity was assumed ($L = 50$ cm, $\Gamma = 4$ (ns)$^{-1}$, $x_0 = 50$ μm, a = 0.2 cm). The solid and dashed lines show Hu's steady-state results.
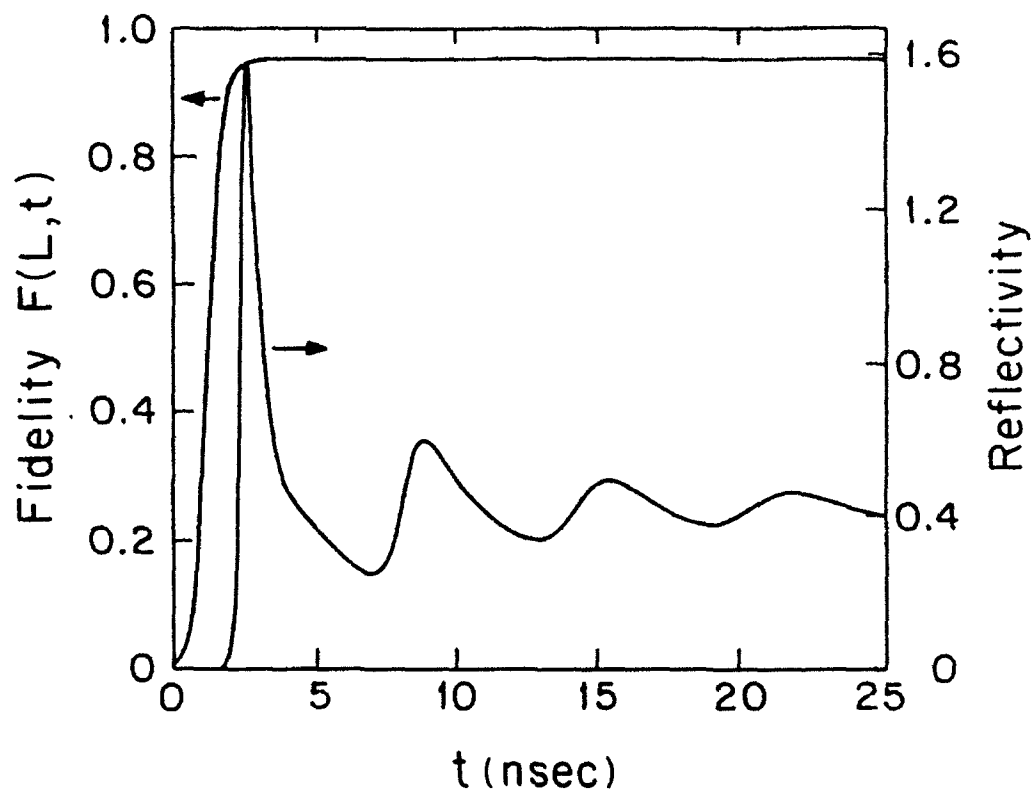
Figure 8. Transient reflectivity and fidelity for gL = 20 (L = 50 cm, Γ = 4 (ns)$^{-1}$, x_0 = 50 μm, a = 0.2 cm).

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